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Maximum window-to-wall ratio of a thermally autonomous building as a function of envelope *U*-value and ambient temperature amplitude

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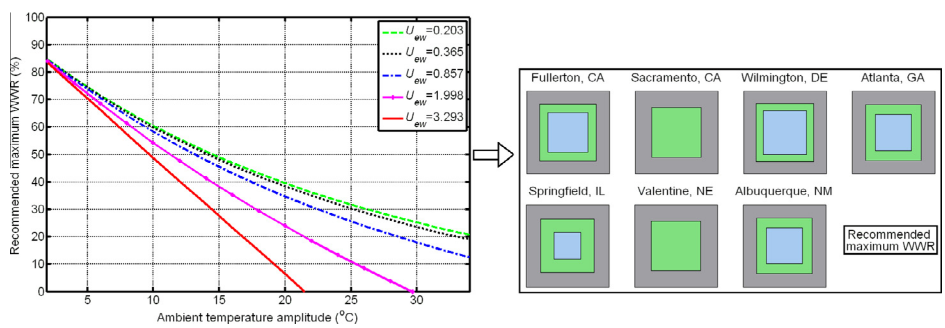
HIGHLIGHTS

- Investigated the max WWR as a function of envelope *U*-value and ambient *T* amplitude.
- Obtained the max WWR of seven US cities using the conclusions of this investigation.
- Point out good envelope is more important in locations with large ambient *T* amplitude.

GRAPHICAL ABSTRACT



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ABSTRACT

In two earlier papers we proposed a *process assumption-based design* method, one aim of which is the determination of the thermal requirement of a building by investigating the building functioning as a dynamic thermal system. The principal constraint of that determination is the building indoor temperature range to be no more than 2 °C. In this paper we focus on the thermal requirement of maximum WWR (window-to-wall ratio) allowed by the constraint as a function of envelope *U*-value and ambient temperature amplitude. Seven US cities are studied to represent a range of ambient temperature amplitudes. As the window part of a building's envelope is a prominent architectural feature of the building, WWR and its allowed maximum in terms of thermal autonomy are the signature/reflection of local ambient temperature amplitude and the variety of envelopes of building stock in each locality. Such signal characteristics are otherwise referred to as regional architecture.

1. Introduction

The conventional *heat balance* design method calculates a building's thermal performance for determining a building's heat import (or heat removal) requirement for sizing HVAC system: as *ASHRAE Handbook* notes, "[peak design] heating and cooling load calculations are the primary design basis for most heating and air-conditioning systems and components. These calculations affect the size of piping, ductwork, diffusers, air handlers, boilers, chillers, coils, compressors, fans, and every other component of systems that condition indoor environments" [1]. One key assumed constant of the ASHRAE balance method is the specific indoor air temperature: 20 °C db in winter (correspondingly, 24 °C db in summer). Implicit in the heat balance design is the traditional sequential design paradigm, "where the architect designs the building shape, orientation and envelope and then transmits

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the drawings to the mechanical and electrical engineers for their design [in] a sequential approach" (Bellenger's 2010–11 ASHRAE Presidential Address [2]). In her address, Bellenger called for a new paradigm of integrated design. In two recent papers [3,4], we proposed a *process assumption-based design* method, a two-step design method, the first (architectural) step of which treats a building's thermal performance, not for sizing HVAC system, but for determining a building's architectural requirement with the objective of building thermal autonomy in its temperature range. This first step requires the collaborative effort of architects and engineers. The second engineering step then determines how the building will be linked to its environment with the objective of building thermal homeostasis in its temperature level. Process assumption-based design shows promise of capturing the spirit of integrated design: what remains sequential being the logical nature (first range then level) in design steps, not the temporal order (first architects then engineers) in design professions' segregated practices.

The idea of the architectural step originated from a 2013 paper [3], in which the concept of *neutral* mean ambient temperature $(\bar{T}_0)_{\text{neutral}}$ was introduced. Consider an assumed sinusoidal diurnal variation in ambient hourly temperature $T_0(t)$, where ΔT_0 is the ambient temperature amplitude:

$$T_0(t) = \bar{T}_0 + \frac{1}{2}\Delta T_0 \sin\left(2\pi \frac{t[\text{hr}]}{24}\right) \tag{1}$$

$(\bar{T}_0)_{\text{neutral}}$ is defined as the mean ambient temperature level that the envelope heat transmission loss is balanced with internal heat gain so that no HVAC equipment operation is required. The paper then focused on the investigation of the architectural requirement in envelope resistance and thermal mass so that the indoor operative temperature stays within a given temperature range.

That line of ad hoc approach was generalized, in a second paper [4], into the *process assumption-based design* method: By formally conceiving the design as a two-step process with the first architectural step focusing on the indoor operative temperature *range* as the design constraint and the second mechanical-engineering step devoted to maintaining the indoor operative temperature *level* as the design objective, the authors of the second paper outlined a design approach free of the artificial restriction of neutral mean ambient temperature. In the process design method, building energy is not exclusively a heating or cooling load demand issue that requires energy or power supply for meeting its demand – but a building thermal processes problem, or how a building interacts thermally with its ambient environment. This latter approach invites inquiry of *architectural solutions* – as well as active engineering solutions involving both stock energy (energy forms that we sell and buy) and natural energy (energy forms that are free). Whereas the architectural consideration points to the passive role of building envelope on controlling loads, the engineering solutions suggest that building thermal mass and effectiveness in heat transfer systems are of equally significant roles in the active management of heat.

One specific result of the second paper [4] was the discovery that for a building with adequate internal thermal mass/wall thermal mass and with constant wall-envelope thermal resistance, the design goal of building thermal autonomy (building maintaining its acceptable indoor operative temperature range with no HVAC equipment) yielded a functional relationship between maximum (window-to-wall ratio) WWR and ambient temperature amplitude—which was a new proposition in building science.

Having just reached that interesting result, we now turn our attention to transforming the promise of process assumption-based design outlined in [4] to becoming a new design paradigm. For that goal, process assumption-based design, which is defined by the necessity of active management of heat, needs to demonstrate its value as an application tool and at the same time to be provided with a firm scientific foundation. It needs to demonstrate of being able to generating additional propositions beyond "optimal internal thermal mass" [3] and "functional relationship between maximum WWR and ambient temperature amplitude" [4]. At the same time in another publication [5], we argued thermodynamically why active management or extraction of heat is necessary for achieving efficiency in meeting low-grade heat need in buildings. This paper fulfills the expectation of the former kind by investigating relationship in thermally autonomous buildings between maximum WWRs and the ambient temperature amplitude with different envelope thermal resistances (or their reciprocals – thermal conductivities).

While allowed maximum WWR is the research object of this paper, the reasons for focusing on envelope (specifically walls) thermal conductivity and ambient temperature amplitude as the two major variables in this study are: (1) the wall thermal conductivity (*U*-value) is an important control variable in the *ANSI/ASHRAE/IES Standard 90.1* [6] (see Section 3) and has a great effect on the maximum WWR (see Fig. 6 below); (2) the ambient temperature amplitude is a rarely investigated variable and we have not found any literature except our own Ref. [4], which identified it as a principal variable on allowed maximum WWR (see also Fig. 6); (3) the roof/floor *U*-value is much smaller than the wall *U*-value according to the *Standard 90.1* [6] and the pattern of the effect on the conclusions from the roof/floor *U*-value should be similar to that from the wall *U*-value, but should be with smaller effect; (4) factors that are heat gain related, such as internal heat gain, window SHGC (solar heat gain coefficient), shading, sky cloudiness and building orientation, do has a great impact on the maximum WWR; however, it is neither possible nor necessary to present all the factors in one paper, and as a case study, it should be acceptable to control these factors by assuming them with reasonable values; (5) the occupant behaviors (including window/door opening by occupants) are quite complicated and uncontrollable, and thus it will not be considered in this paper; (6) the thermal mass was extensively investigated in Ref. [4].

In Section 2, the previously developed RC (resistor–capacitor) model [3,4,7] will be described briefly. The model is then used in Section 3 to investigate the maximum WWR as a function of ambient temperature amplitude and exterior envelope thermal conductivity (i.e., exterior wall *U*-value). In Section 4, seven cities, which represent a wide geographic range of the United States, will be selected and their ambient conditions in summers will be analyzed. Section 5 presents maximum WWRs for the seven cities based on the design diurnal temperature amplitude ($\Delta T_{0\_\text{design}}$) of these cities. We close the paper with a summary of the arguments and the potential implication of the new findings.

Notice that this paper does not aim to obtain "accurate" WWRs of buildings, but to give guidelines (see Sections 3 and 5) to designers for determining the "maximum" WWRs considering building envelope *U*-value and diurnal ambient temperature amplitude. Three major reasons are: (1) it is very hard to investigate all the factors in one paper; (2) every building is unique and in order to design a high performance building, nearly all of the major factors need to be considered in the design process; (3) the factors are often interrelated and tradeoffs are usually involved in the process of designing a building. Therefore, accurate WWRs of buildings in fact cannot be obtained in a case study, and thus this study aims to give the "limits" of WWRs rather than "accurate" WWRs. The value of such WWR limits is the prediction made in this paper of very different architectural variety in terms of the range of WWRs and the required envelope *U*-values on the basis of envelope thermal conductivity and ambient temperature amplitude as the only major variables.

2. RC model of a building-room

In Matlab and Matlab/Simulink, Refs. [3,4,7] developed an RC model of a south-west corner room in an office building located in Zürich, Switzerland. The floor plan and a southwest corner view of the building are shown in Figs. 1 and 2, respectively. The configuration of the modeled office building [8] is chosen according to typical characteristics of TABS-equipped office buildings. The building has two main orientations (south and north) with normal offices along the main façades and corner offices with glazing on two sides at the front faces. The building has five stories and each story has twelve normal offices and four corner offices. Each office has dimensions of 6 m × 6 m × 3 m, and the total floor area is 2880 m^2. All ceilings and floors are constructed of concrete slabs with PEX pipes inside, i.e., TABS, which is a successful strain of hydronic radiant conditioning systems.

The RC model on building energy simulations has been used and validated in a large volume of literature [8–16]. In the RC model, "thermal resistor" is modeled as resistor, "heat capacity" is capacitor, "temperature" is voltage, and "heat gain" is current. The RC model is so flexible that it is an ideal tool for parameter studies of buildings. Whereas computer-aided modeling in advanced software (such as TRNSYS, EnergyPlus, ESP-r, Trane TRACE and eQuest) is useful for taking into consideration of detailed and specified design features of individual buildings when their major design decisions on the system level are made on sound building physics, the RC modeling is the simulation tool (like the classical experimental tools) that can generate dependent outcomes over a range of experimental parameters, yielding in the first place those building physics propositions that guide major design decisions of buildings.

In the south-west corner room, only the south- and west-facing walls are exposed to the outdoor surroundings. The external walls consist of 10 cm-thick normal-weight concrete and insulation outside of the concrete. The other two walls, the ceiling and the floor are considered as interior thermal mass (iTM). The slabs in the ceiling and floor are 25 cm-thick normal-weight concrete. The internal walls are made of 20 cm-thick structural light-weight concrete. Other interior thermal mass are modeled as wood with dimensions of 6 m × 6 m × 0.1 m. All the windows are double glazing with low-E coating. The room has a large WWR of 42%. The thermal resistance of the windows is 0.53 m^2 K/W and thus the thermal conductivity is 1.887 W/m^2 K, which is smaller than the restricted maximum *U*-value (1.99 W/m^2 K for Climate Zone 5) in the *Standard 90.1-2010* [6].

The total air change rate of infiltration and ventilation for the room is 0.7 ACH, which meets the requirement for indoor air quality. The heat gains of the room include solar energy input q_s'' and internal heat gain q_i''. The solar input is calculated from the solar geometry of Zürich, assuming that 8% goes through the windows because of the good external shading. Internal heat gain includes the heat dissipation from lighting, persons, and equipment.

Based on the descriptions above, the RC model of the room is shown in Fig. 3. The modules of the internal walls, other interior thermal mass and the internal heat gain are all in the "Building inside" module. The TABS module is in the RC model, but it is disconnected here because this investigation on the allowed maximum WWR is part of the first architectural step. In other words, the HVAC system (that is, TABS here) though included in the model is not activated (cooled or heated) in the following simulations. The sizing of the HVAC system was investigated as the second step in another paper [17]. That is, in this study, the indoor temperature is floating (flowing) since there is no heating and cooling equipment operation for the room. The sample time is 60 s, and using a typical personal computer, the simulating duration of the room on a design day is about several minutes.

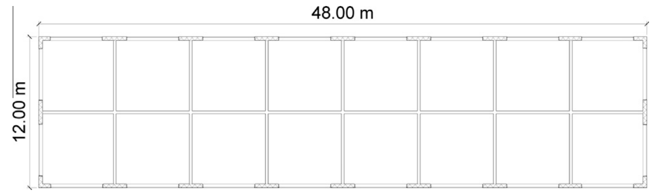

Fig. 1. Floor plan of the building.

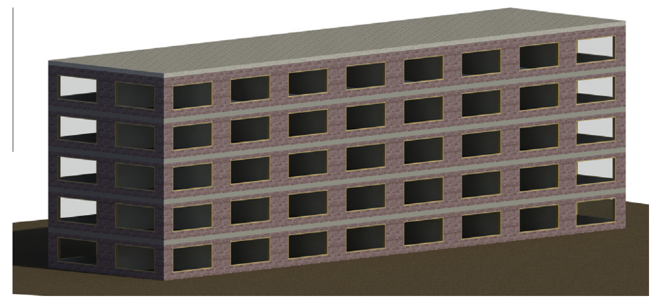

Fig. 2. Southwest corner view of the building.

Having described the thermal modeling of the room, in the next section, we will apply the modeling to investigate the building as a thermal system in interaction with its surroundings in order to determine the maximum WWR as a function of ambient temperature amplitude and exterior envelope *U*-value.

3. Maximum WWR under different ambient temperature amplitudes and exterior envelope *U*-values

The fenestration WWR defined as "the ratio of the transparent glazing area to the outdoor floor-to-floor wall area" [18] is an important parameter for controlling the indoor operative temperature variation within a small range. According to Ref. [19], "wall" in WWR is defined differently in the *Standard 90.1-2010* [6] and the *2012 IECC* (International Energy Conservation Code) [20]. In the *Standard 90.1-2010*, a wall area of both above and below-grade "walls" is the denominator of WWR. Chapter 5 of the *2012 IECC* considers only above-grade walls. Here we follow the definition in the *2012 IECC*. Note that "the outdoor floor-to-floor wall area" also includes the window area, which means that if the WWR is 100%, there in fact is only window, rather than half window and half wall. Fig. 4 gives an intuitive view of the WWR.

The modeling conditions and the parameter selection of the investigated room are:

(a) The mean value of the ambient temperature T_{out} is 27.10 °C (300.25 K). This selection is for convenience only, since it is the summer mean T_{out} of the seven cities that will be investigated in Section 4 below. Actually, the mean T_{out} is not important for this study that is focusing on indoor operative temperature amplitude. Our investigation in Ref. [4] shows that the mean T_{out} almost has no influence on the indoor temperature amplitude (see the comparison of Tables 2 and 3 in the reference).

(b) The ambient temperature amplitudes ΔT_{out} are from 2 K to 34 K with a 4 K step. We believe that 2–34 K is a sufficiently wide range that should cover most diurnal ambient

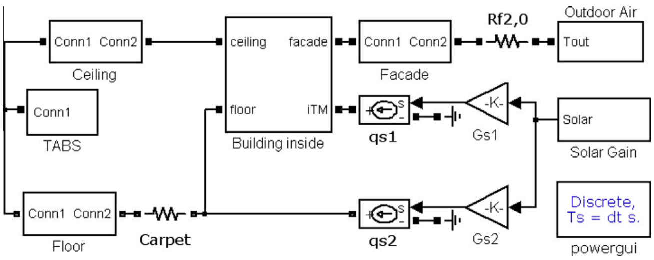

Fig. 3. RC model of the room built in Simulink.

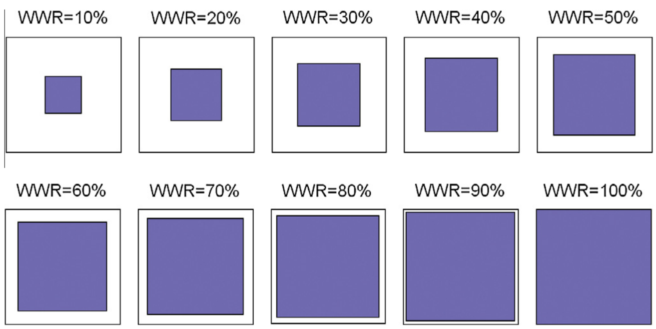

Fig. 4. Window-to-wall area ratio in percentage.

temperature amplitudes in the world for generalizing our investigation; and 4 K is a reasonable step considering the coverage and computing complexity.

(c) The WWR are 20%, 40% and 60%.

(d) The five U-values of the external walls are [6,21,22]:

$\boldsymbol{U_{ew}}$ = **3.293** W/m^2 K: Maximum restriction of nonresidential mass walls (Zones 1–2 in *Standard 90.1-2004*; Zone 1 in *Standard 90.1-2007* and *2010*); Maximum restriction of semi-heated mass walls (Zones 1–7 in *Standard 90.1-2004*; Zones 1–4 in *Standard 90.1-2007* and *2010*).

$\boldsymbol{U_{ew}}$ = **1.998** W/m^2 K: Maximum restriction of semi-heated steel-framed walls (Zones 1–3 in *Standard 90.1-2004*; Zone 1 in *Standard 90.1-2007* and *2010*).

$\boldsymbol{U_{ew}}$ = **0.857** W/m^2 K: Maximum restriction of nonresidential mass walls (Zones 3–4 in *Standard 90.1-2004*; Zone 2 in *Standard 90.1-2007* and *2010*); Maximum restriction of residential mass walls (Zones 1–2 in *Standard 90.1-2004*; Zone 1 in *Standard 90.1-2007* and *2010*); Maximum restriction of semi-heated mass walls (Zone 8 in *Standard 90.1-2004*; Zones 5–6 in *Standard 90.1-2007* and *2010*).

$\boldsymbol{U_{ew}}$ = **0.365** W/m^2 K: Maximum restriction of nonresidential mass walls (Zone 1 in *Standard 90.1-2004*); Maximum restriction of nonresidential steel-framed walls (Zones 7–8 in *Standard 90.1-2004*; Zones 4–8 in *Standard 90.1-2007* and *2010*); Maximum restriction of nonresidential wood-framed and other walls (Zone 5 in *Standard 90.1-2007* and *2010*); Maximum restriction of residential steel-framed walls (Zones 4–7 in *Standard 90.1-2004*; Zones 2–6 in *Standard 90.1-2007* and *2010*); Maximum restriction of residential wood-framed and other walls (Zone 6 in *Standard 90.1-2004*; Zone 4 in *Standard 90.1-2007* and *2010*).

$\boldsymbol{U_{ew}}$ = **0.203** W/m^2 K: Maximum restriction of nonresidential wood-framed and other walls (Zone 8 in *Standard 90.1-2007* and *2010*); Maximum restriction of residential wood-framed and other walls (Zone 8 in *Standard 90.1-2007* and *2010*).

Notice that Zones 1–2 mean very hot and hot climates, respectively, such as Hawaii and Florida. U_{ew} = 3.293 W/m^2 K for these two zones is really a high value. Zones 7–8 mean very cold and subarctic climates, respectively. All of Alaska is in Zone 7 except

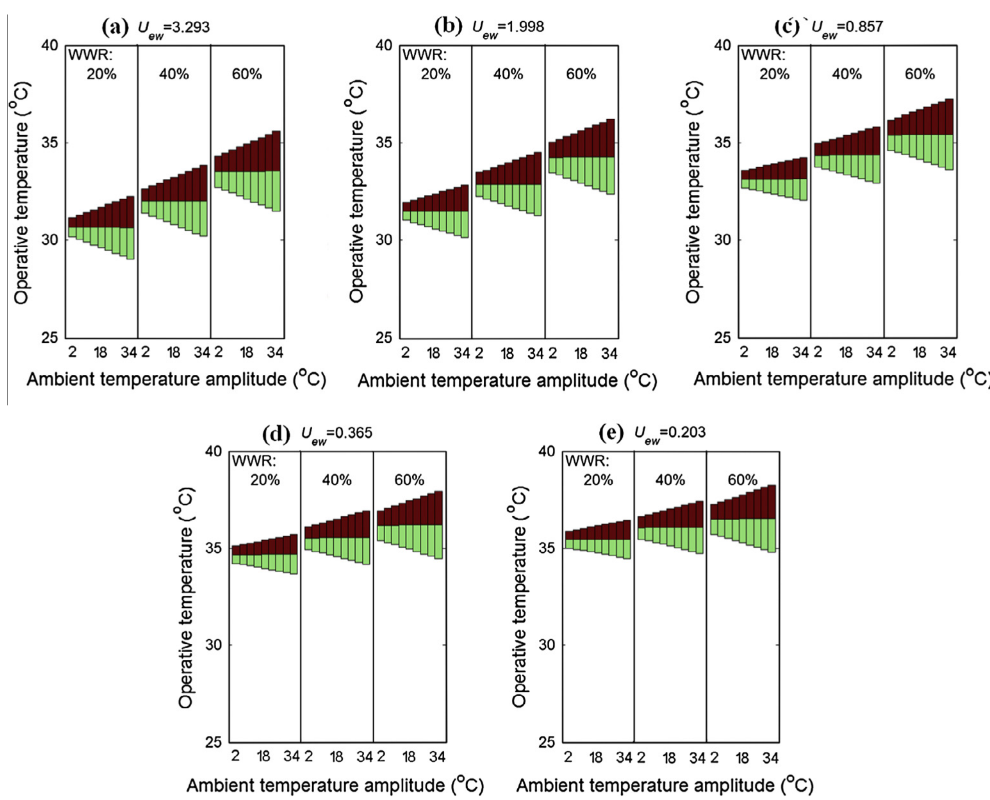

Fig. 5. Operative temperatures under different WWR and U_{ew}.

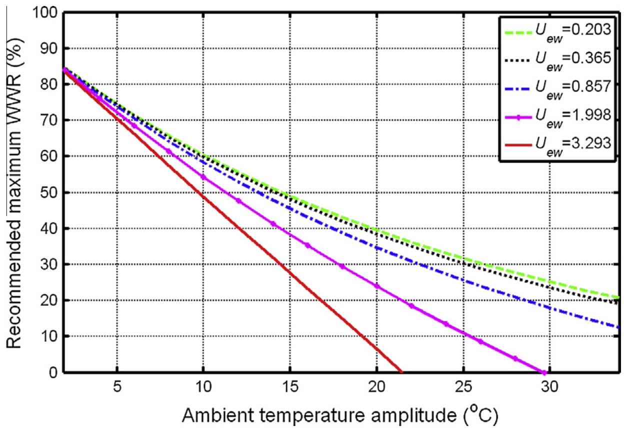

Fig. 6. Maximum WWR (%) as a function of ΔT_{out} and U_{ew}.

for several boroughs in Zone 8. Therefore, $U_{ew} = 0.203\ W/m^2\ K$ is undoubtedly a low value.

The operative temperatures under different WWR and exterior envelope U-values are shown in Fig. 5. In the figure, there are total 135 cases (5 U_{ew}, 3 WWR and 9 ΔT_{out}). While U_{ew} and WWR are fixed, ΔT_{op} increase obviously with larger ΔT_{out} for all cases; while U_{ew} and ΔT_{out} are fixed, bigger WWR causes larger ΔT_{op}; while WWR and ΔT_{out} are fixed, with the increase of U_{ew}, ΔT_{op} become larger. The reason of these phenomena is the same: with the increase of U_{ew}, WWR and ΔT_{out}, the influence of the outdoor environment on the indoor environment becomes bigger as a result of greater heat exchange across the envelope.

In Fig. 5, the mean values of operative temperature vary a lot when the U_{ew} and WWR are changed. This is because the balance in the 24 h period between the solar energy input and the envelope heat transfer is changed with the modification of the building envelope. However, this is not the research point of this paper (which is the first step of process assumption-based design). When the HVAC system works properly, the operative temperature level will be maintained in the comfortably low range. Notice that the operative temperature level shown in Fig. 5 is in fact lower with higher U-value though that has a negative impact on the operative temperature range as it can also be seen in Fig. 6.

Using the criteria [3,4] that the maximum ΔT_{op} is kept at or below 2 K, the maximum WWR as a function of ΔT_{out} and U_{ew} are shown in Fig. 6. Maximum WWR decreases sharply with the increase of ΔT_{out} for high U_{ew}. That is why ΔT_{out} is treated as an important impact factor in building design in [3,4] and this paper. With better exterior envelope (i.e., smaller U_{ew}), building can have a bigger allowed WWR and thus occupants shall have better perceived aesthetics. However, benefit in further reducing U_{ew} becomes negligible when the exterior envelope U-value is sufficiently small, for instance comparing the cases of U-values 0.203 and 0.365.

As WWR is a prominent architectural feature of a building, the result is interesting in terms of WWR as the signature/reflection of local ambient temperature amplitude and the variety of envelopes of building stock in each locality. Such signal characteristics are otherwise referred to as regional architecture. A number of conclusions may be drawn from Fig. 6:

(1) At locations of small ambient temperature amplitude large WWR on average and a narrower variation in WWR are expected while at locations of large ambient temperature amplitude small WWR on average and a wider variation in WWR are expected.
(2) Since envelope performance improves over time, a general increase in WWR is expected. Increase in WWR over time, however, is more prominent in areas of large ambient temperature amplitude.
(3) A general increase in WWR is expected over locations as their ambient temperature amplitudes become gradually smaller. This trend, however, can be partially distorted by the variety of envelopes of building stocks.

An example of Conclusion (1) will be given in Sections 4 and 5 by investigating the maximum WWR of seven selected US cities under design diurnal temperature amplitudes.

4. Ambient summer conditions of seven US cities

In these two sections (this and the next), the maximum WWR of seven cities in the United States will be predicted according to the study and the ambient summer conditions of the cities. As shown in Fig. 7, the cities are: Fullerton, CA; Sacramento, CA; Wilmington, DE; Atlanta, GA; Springfield, IL; Valentine, NE; and Albuquerque,

Fig. 7. Distribution of the selected seven US cities (made in http://maps.google.com).

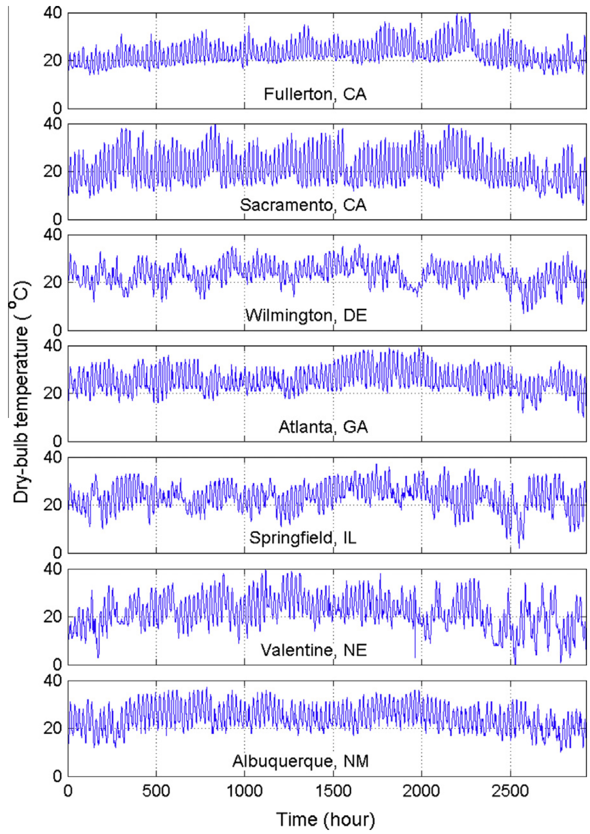

Fig. 8. Dry-bulb temperatures of the selected seven US cities in the summer of 2007.

NM. From the figure, it is clear that the distribution of the cities can well represent a wide geographic range of the United States.

To investigate the ambient temperature characteristics of the seven cities, the real-time hour-by-hour dry-bulb temperatures of the cities are shown in Fig. 8, which were requested by email from the website of the US Department of Energy (DOE) [23]. The data are collected by the National Weather Service (NWS) from weather stations, and are parsed and stored into a local database at the National Renewable Energy Laboratory (NREL) [24]. Some data in the weather database are missing, and upon request the missing data are exported with interpolated values (for the dew point and the dry bulb temperatures only). If the missing period is less than 6 h, the data are simply filled linearly; if it is more than 6 h and less than 48 h, the data are filled by taking the trend of the first previous day that is valid; if it is more than 48 h, the program creates a new file where the data starts again [24]. In the recent decade, 2007 is the only year that all the four-month summer weather data are in one file, that is, all the missing periods are less than 48 h. The accumulative hours of missing periods in the four months are from 46 h to 77 h.

Conventionally, the design of HVAC equipment is based on a fixed "climatic design [peak] conditions," which for annual cooling according to the *ASHRAE Handbook – Fundamentals* [18] is the *design condition for 0.4%* or the *design condition for 1%* or the *design condition for 2%* in annual cumulative frequency of occurrence (exceeding the design condition) in one year. There are 365×24 h = 8760 h in one year. The *0.4%*, *1%*, and *2%* design conditions are the three dry-bulb temperatures T_0 values that the instantaneous hourly temperature in the hottest months exceeded the corresponding value for a duration of 35 h (0.4% of 8760 h), 88 h (1%), or 175 h (2%) per year, respectively, for the period of record. For convenience the following discussion will be based on 1% dry-bulb temperatures T_0 or $(T_0)_{\text{design\_1\%}}$. We may have the relationship

$$T_0 = \bar{T}_0 + \frac{1}{2}\Delta T_0 \tag{2}$$

where $\bar{T}_0$ is the daily mean temperature and ΔT_0 is the peak-to-peak amplitude of the diurnal temperature. T_0 depends on (and increases with) both the daily mean temperature and its amplitude.

According to the *ASHRAE Handbook* [18], the summer months are the months from June through September, a period of 122 days or 2928 h. For the seven cities in the hottest month, the mean ambient 1% dry-bulb temperatures are between 300.2 K and 300.3 K, and the corresponding mean amplitudes are between 9.5 K (Wilmington) and 18.1 K (Sacramento), as shown in Table 1. The reason of the selection is that the seven cities' design 1% daily-mean dry-bulb temperature may be taken to a constant of 300.25 K (**27.10 °C** or 80.78 °F), as the *mean design condition for 1%*, $(\bar{T}_0)_{\text{design\_1\%}}$. In this case, $(T_0)_{\text{design\_1\%}}$ depends only on the daily mean temperature amplitude.

Using the real-time weather data, the distribution histograms of the 122 diurnal temperature amplitudes of each city are calculated and shown in Fig. 9. For each city, the amplitude is defined by the temperature difference of the maxima and the minima in the duration from midnight to the next midnight. In the figure, if the amplitude is not an integer, it is rounded. From the figure, it can be found: (1) most amplitudes are smaller than 20 °C in most cities, except a very small part in Springfield, a small part in Valentine and a moderate part in Sacramento; (2) amplitudes are mainly distributed in the large-amplitude part in Sacramento; (3)

Table 1
Design conditions for the selected US cities (from *2009 ASHRAE handbook*).

Location	Climate zone	Design 1% hourly dry-bulb temperature ("peak"), $(T_0)_{\text{design\_1\%}}$		Mean daily dry-bulb temperature range, ΔT_{0_mean}		Design 1% daily-mean dry-bulb temperature, $(\bar{T}_0)_{\text{design\_1\%}}$	
		°F	K	°F	K	°F	K
Fullerton, CA	3B	90.1	305.4	19.0	10.6	80.6	300.2
Sacramento, CA	3B	97.1	309.3	32.6	18.1	80.8	300.3
Wilmington, DE	4A	89.3	305.0	17.1	9.5	80.8	300.2
Atlanta, GA	3A	90.7	305.8	19.9	11.1	80.8	300.2
Springfield, IL	5A	90.5	305.7	19.3	10.7	80.9	300.3
Valentine, NE	5A	94.0	307.6	26.4	14.7	80.8	300.3
Albuquerque, NM	5B	92.9	307.0	24.4	13.6	80.7	300.2

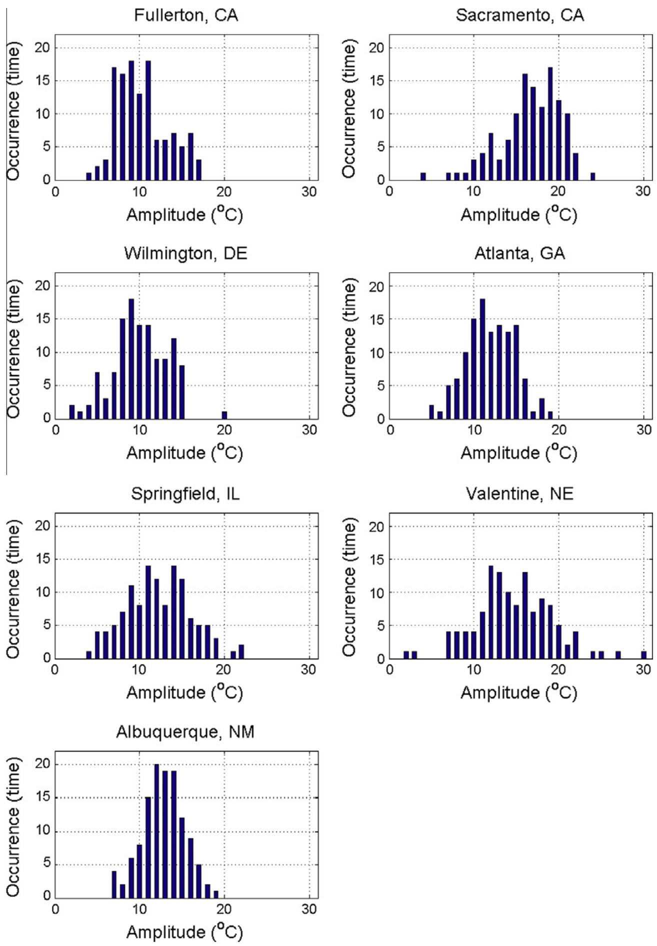

Fig. 9. Dry-bulb temperature amplitude distributions of the selected seven US cities in the summer of 2007.

in other cities, amplitudes are mainly distributed in the middle- or small-amplitude part.

5. Maximum WWR and design diurnal temperature amplitude

Let us select the fifth highest temperature amplitude in the summer months of 2007 as the design diurnal temperature amplitude (ΔT_{0_design}), as listed in Table 2. The recommended maximum WWR of the seven cities, also shown in Fig. 10, are obtained from Fig. 6 with ΔT_{0_design} as the control parameter. The maximum temperature amplitudes in the four summer months of 2007, the mean values of the ambient temperatures in the hottest month of 2007 and the mean values of the ambient temperatures in the hottest month from the *ASHRAE Handbook* are also listed in Table 2. As seen from the table, in the hottest month of 2007, the mean values of the ambient temperatures are higher than the corresponding values from the *ASHRAE Handbook*, except in Sacramento, CA.

Fig. 10. Maximum WWR of the selected US cities under the design diurnal temperature amplitudes.

For each sub-figure in Fig. 10, the largest square colored in gray represents the area of the whole building vertical envelope; the smallest square colored in sky-blue represents the maximum window area when $U_{ew} = 3.293$ W/m^2 K, the ratio of the two areas being the WWR and representing the lower bound of maximum WWR. When U_{ew} decreases to 0.203 W/m^2 K, the maximum window area can be enlarged to the boundary of the mid-size square, representing the upper bound of maximum WWR. Therefore, as the exterior envelope *U*-value varies between the two extreme values, the maximum window area correspondingly varies in the light-green region. Notice that in Sacramento and Valentine, there is no sky-blue square, which means that no window is even allowed if the envelope has a really big *U*-value, the necessity of high-performance envelope with small *U*-value; it appears that the result means that one can expect a wider variation in WWR in these locations dependent on the quality of building envelope. On the other hand, our result indicates that smaller variation in WWR may be expected of buildings in Fullerton and Wilmington of varying envelope qualities due to their temperate temperature amplitude.

An additional conclusion can be made from Fig. 10:

(4) Low *U*-value, high performance envelope is more important in locations of large ambient temperature amplitude such as

Table 2
Design diurnal temperature amplitudes and maximum WWRs of the selected US cities.

Location	ΔT_{0_design} (K)	Recommended maximum WWR (%)	ΔT_{0_max} in the four months, 2007 (K)	ΔT_{0_mean} in the hottest month, 2007 (K)	ΔT_{0_mean} in the hottest month from *ASHRAE Handbook* (K)
Fullerton, CA	16.1	22.88–46.71	17.2	11.2	10.6
Sacramento, CA	22.0	0–36.20	24.0	17.5	18.1
Wilmington, DE	15.0	27.55–48.95	20.0	11.8	9.5
Atlanta, GA	17.0	19.10–45.00	19.0	13.1	11.1
Springfield, IL	19.0	10.65–41.30	22.0	14.9	10.7
Valentine, NE	22.2	0–35.90	30.0	16.4	14.7
Albuquerque, NM	17.0	19.10–45.00	19.0	14.4	13.6

Sacramento and Valentine for reason of building thermal autonomy as well as the usual reason of cooling and heating load control.

6. Conclusion

Building energy issue is usually treated as an energy demand and supply problem, in which the heat balance design method is applied once the architectural decision of a building has been made for calculating loads and selecting HVAC systems. The conventional approach overlooks the opportunity of treating buildings as thermal systems. We have proposed a different design method, the process assumption-based design method [3,4]. This paper continues the line of investigation by determining relationship in thermally autonomous buildings between maximum WWRs and the ambient temperature amplitudes with different envelope thermal resistances. Useful conclusions are made in Figs. 6 and 10, which demonstrate the utility of the process assumption-based design in understanding buildings as dynamic thermal systems and their architectural thermal requirement in achieving thermal autonomy of acceptable temperature range. As shown in Fig. 10, very different architectural variety in terms of the range of WWRs and the required envelope *U*-values is predicted on the basis of envelope thermal conductivity and ambient temperature amplitude as the only major variables on maximum WWR in the seven cities. This finding suggests possible investigations for future study: Firstly, an architectural survey may be conducted in the seven cities with two possible outcomes (other outcome is also possible). A positive statistical correlation will validate the utility of process assumption-based design method and the fact that thermal autonomy is an implicit factor in building design statistically. A negative correlation may suggest that either that thermal autonomy has not been a factor in building design (though it should be) or variable(s) other than envelope thermal conductivity and ambient temperature amplitude is important variable for WWR decision, which has been overlooked in this study and should be investigated for future consideration. This seems to be an excellent example of what Bellenger called a new paradigm of integrated (architectural and engineering) design (and research).

This paper focuses on the problem of maximum WWR based on the temperature range constraint and will be accompanied with another paper [17] for determining the engineering requirement in achieving thermal homeostasis of acceptable temperature level. Our ultimate goal is to demonstrate the utility of process assumption-based design alongside heat balance design as the tool for achieving real building energy saving.

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